Personalized conditioning with human-in-the-loop control approach

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ABSTRACT

The need for individual comfort led to the development of personalized conditioning systems which improve the thermal comfort and allow to reduce energy consumption due to more effective localized energy use. However, the process control of such systems is still rather traditional and not optimal. The skin temperature of the hands plays a prominent role in thermal comfort in cool environments. Since the hands are directly exposed to the environment their temperature can be remotely sensed and used for control in human-in-the-loop approach. A recent study showed the potential of such a process control. The change in thermal comfort was feed-forwarded by the fingertip temperature drop which was used as a control signal for infrared hand heating lamps. In this paper the limitations of the previous study are discussed and the future research directions are given.

Keywords: heating, personalized conditioning, thermal comfort

INTRODUCTION

The traditional approach to heating, ventilation and air conditioning (HVAC) design aims to create uniform conditions in the entire conditioned space. The requirements for indoor environment prescribed in the currently used standards like ISO 7730 or ASHRAE 55 (International Standard Organisation 2005; ASHRAE 2004) are based on the average values for a large group of occupants. However, in practice the individual differences based on many factors including age, gender, clothing, activity or individual preferences make it impossible to satisfy the comfort needs of all the occupants using a total volume conditioning. Furthermore only few body parts are usually the source of thermal discomfort, typically head in warm environments and hands and feet in cool environments (Yao et al. 2007; Zhang, Arens, Huizenga, et al. 2010). These facts led many researchers to designing of a personalized conditioning system.

Different personalized conditioning systems were introduced, including personalized ventilation (Melikov 2004), combination of personalized ventilation with local convective and radiant heating (Melikov & Knudsen 2007; Watanabe et al. 2010) or personal environmental module (Demeter & Wichman 1993). These systems not only have positive impact on thermal comfort and indoor air quality, but also have a good potential for energy reductions. Personalized ventilation with a proper control strategy makes it possible to reduce energy use in hot (Schiavon et al. 2010) as well as in cold climates (Schiavon & Melikov 2009). Zhang et al. (2010) reported simulated annual heating and cooling energy savings of as much as 40 % by extending the indoor dead-band to 18 to 30 °C with a use of a low power task ambient conditioning system.

A crucial aspect influencing the performance of any personalized conditioning system is the individual control provided to its user. The users are often provided with the control over their personalized air flow, temperature of this air flow or temperature of the heating elements. However, this way of control is still highly dependent on the occupants' behaviour and can often lead to decreased comfort level and increased energy use. It is therefore desirable to control the conditioning by a critical parameter predicting the changes in occupants' comfort.

Since the hands dictate the thermal comfort in cool environments (Arens & Zhang 2006), the hand skin temperature can become a critical parameter for control of a local heating system. This paper presents results of a study of a "human in the loop" control approach, where the remotely sensed fingertip temperature is used as a control signal for the local radiant hand heating. The limitations of the presented study and future research directions are discussed.

HUMAN THERMOREGULATION AND THE IMPORTANCE OF THE BODY EXTREMITIES

Although the human body can be exposed to a wide range of thermal environments comprising temperatures from about -40 °C in arctic areas up to +100 °C in sauna it normally keeps its core temperature in a small range of 36 – 38 °C. Human skin representing the boundary between the human body and its surrounding environment is the major organ which plays a role in the body thermoregulation. The human thermoregulation consists from three main components – thermoreception, its integration through neural pathways and effective response of the organism in terms of heat loss or heat production (Kingma 2012).

The body does not sense directly the temperature of its environment. The thermal sensation is instead coded in the fire rate of cold and warm receptors contained in human skin (Kingma 2012). The temperature information is then passed to the hypothalamus in the brain, where the autonomic thermoregulation is activated. Each of the thermo receptors is activated in a specific range of temperatures, the textbook of medical physiology (Guyton & Hall 2000) states that the maximum fire rates lie for cold receptors at 25 °C and for warm receptors at 44 °C. Moreover, the thermal sensation is influenced by time dependent change in skin temperature. The active falling or rising of the skin temperature causes much colder or warmer sensation compared to steady conditions. This overreaction is called 'overshoot' (Arens & Zhang 2006).

Different thermoregulatory principles are applied within and outside the thermoneutral zone. The thermoneutral zone is defined as the range of ambient temperatures without regulatory changes in metabolic heat production or evaporative heat loss (Kingma 2012). The main thermoregulatory principle applied within the thermoneutral zone is thus vasomotion (vasoconstriction and vasodilatation), while outside the thermoneutral zone the human body either produces more heat via shivering or loses more heat via evaporation of the sweat. Vasomotion represents a principle of controlling the heat flow within the body by dilating (vasodilatation) or constricting (vasoconstriction) of the blood vessels, more or less heat is then transported by the blood to the skin where it dissipates to the environment. Since staying within or close to thermoneutral zone is essential for the thermal comfort, vasomotion is important aspect to be considered while designing personalized conditioning systems.

The hand is probably the most active body part in responding to the body's thermoregulatory requirements. In cool conditions, the hand is fully vasoconstricted and the fingertips are the coldest areas of the hand. This pattern is reversed in warm conditions (Arens & Zhang 2006). Wang et al. reported that the finger is a good indicator of the thermal sensation and comfort in cool conditions (Wang et al. 2007). The fingertip temperature (of the 4th finger) of 30 °C was indicated as a threshold for cool discomfort possibility, while above this temperature the thermal sensation is neutral or higher and no cool discomfort occurs.

Thermal sensation and comfort for whole body and local body parts vary greatly in subjects exposed to uniform environments (Arens et al. 2006a; Arens et al. 2006b; Arens & Zhang 2006). Under colder environments the overall thermal sensation and comfort follows the hands and the feet which are perceived as the coldest and the most thermally uncomfortable. Similarly under warmer environments the overall thermal sensation and comfort is determined by the head which is perceived as the warmest and the most thermally uncomfortable. Wang et al. (Wang et al. 2007) reported a substantial improvement of the thermal comfort in cool environments achieved by warming the hands, but the thermal comfort vote was not brought to a positive level. However, these tests covered fairly extreme conditions as found in automobiles. It is likely that under milder conditions hand warming will be able to compensate for the only source of the thermal discomfort.

"HUMAN IN THE LOOP" APPROACH EXPERIMENTS

A study by Vissers (Vissers 2012) tested the hypothesis that cold thermal discomfort can feed forwarded by the drop in the skin temperature of the body extremities such as hands or head. The fingertip temperature was identified to have the most decreasing trend under mild cool office conditions, similar trend with smaller temperature drop was observed for the hand and the nose (Figure 1). Furthermore the skin temperature drop of the body extremities was observed before the actual thermal discomfort was reported by the subject.

The fingertip temperature remotely measured by the infrared thermography was then tested as a signal for a local radiant heating system. Different fingertip temperature bandwidths were tested, but only by controlling the fingertip temperature in a small bandwidth of 29 to 31.5 °C it was generally possible to keep the thermal sensation above the neutral and the subjects did not prefer any change in their thermal environment (Figure 2).

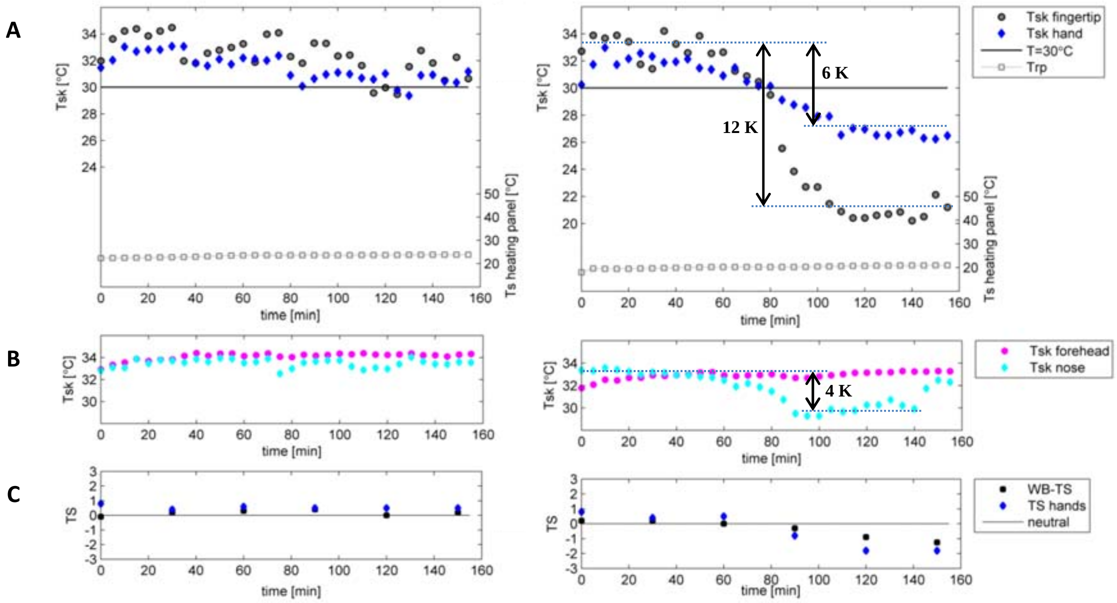

Figure 1 Skin temperatures under neutral (left side; PMV = 0.0) and mild cool (right side; PMV = -0.9) conditions. The fingertip and the hand temperature (A), the forehead and the nose temperature (B) and overall and hand thermal sensation (C) are compared. The temperature drops under mild cool conditions are highlighted. (Vissers 2012)

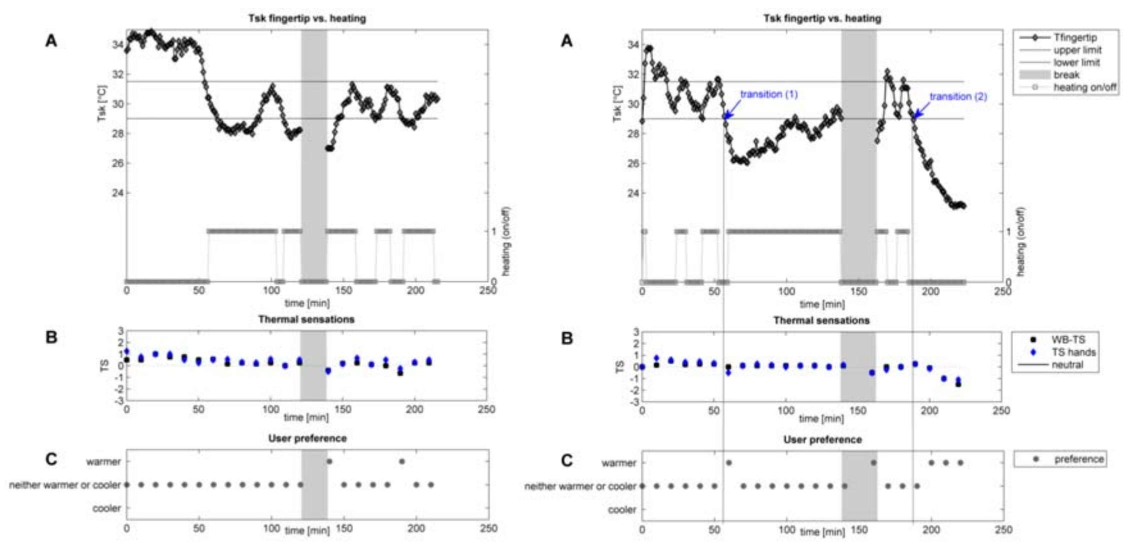

Figure 2 Upper-extremity skin temperature controlled in a small bandwidth: male (left side) and female (right side) subject. The fingertip temperature and the heating signal (A), overall and hand thermal sensation (B) and thermal preferences (C) are compared. (Vissers 2012)

DISCUSSION AND CONCLUSION

Figure 3 presents a comparison of the overall thermal sensation and fingertip temperature as measured in the studies by Wang et al. (2007) and Vissers (2012). This comparison is complicated due to different ranges of ambient temperatures (17.5 – 20.7 °C in Wang's study and 19.6 – 19.9 °C in Vissers') and different heating principles (convective in Wang's study and radiant in Vissers'). However, both studies show an agreement in the fact that keeping the fingertip temperature above 30 °C under mild cool conditions is able to bring the thermal sensation close to neutral and thus avoid the cold discomfort. The previous study by Vissers (2012) did show a potential of using remotely sensed skin temperature as a control for local radiant heating. However, this study was limited to just two test subjects. Since the individual preferences regarding thermal comfort vary greatly among the population it is needed to perform the tests with a larger group of persons.

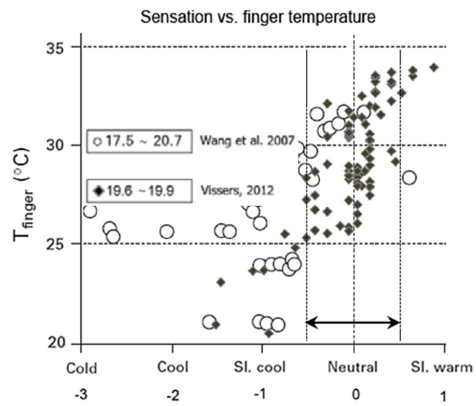

Figure 3 Comparison of the studies by Wang et al. (2007) *and Vissers* (2012)

The way of automatic control represents another limitation of the previous study. In these experiments the following approach was applied. The real-time infrared video signal was observed by the researcher. A certain area of the picture representing the fingertip was then chosen and followed by a computer mouse during whole experimental session. Based on observation of the temperature in the fingertip area the researcher was turning on or off the local radiant heating system to keep the fingertip temperature in a certain bandwidth. This approach served as a proof of a principle and the control was fully automatic from the user point of view. However, the human factor in the control loop could lead to some bias in the experimental results. Moreover, the on/off control can cause an overshoot in thermal sensation. Further tests will thus be performed with automatic finger tracking and using a PID control.

Automatic Finger Tracking

The automatic finger tracking uses pattern matching algorithm from the NI Vision toolkit in LabVIEW. The temperature image from the thermocamera is first transformed to an 8-bit grayscale image. From this image a template corresponding to the fingertip is extracted and the whole image is then searched for the patterns matching this template. An example of this method is shown in Figure 4, where the fingertip of the third finger of the right hand was chosen as a template. In practice it is often a problem to find an appropriate sensitivity setting of the pattern matching algorithm in order to avoid false recognitions. Low sensitivity which avoids false recognitions also makes the algorithm much less sensitive regarding the right recognitions. Following ways how to overcome this problem are tested:

- Searching for more templates in the loop. This allows to decrease the sensitivity, while the chance for a right recognition is increased by the higher number of templates.
- Filtering of the measured values. This allows to exclude the outliers and may identify the false recognitions by too fast time change in the measured temperature.
- Using of moving average will compensate the natural fluctuations in the finger temperature as well as short time periods without the finger recognitions.

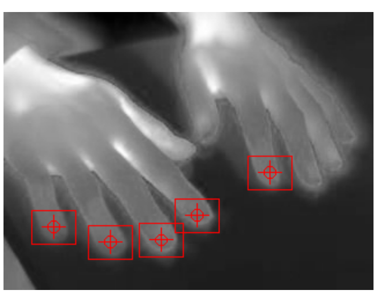

Figure 4 Tracking of the fingers in an infrared image (resolution 320 x 240) using pattern matching in LabVIEW

The current experimental setup uses a very sophisticated thermo camera which is because of its size and high price not suitable for use in the building practice. Therefore the applicability of low cost infrared arrays will be investigated. The low cost infrared array whose resolution may not sufficient for the finger tracking can be coupled with an ordinary optical camera serving just for the tracking.

Individual Differences

Thermal comfort is strongly dependent on individual factors only some of which are considered by current thermal comfort standards. Typically only clothing insulation and activity level are included in thermal comfort equations and other factors such as gender, age or body mass are omitted. A comprehensive literature review on gender differences in thermal comfort by Karjalainen (2012) shows that females are generally more likely to express dissatisfaction with their thermal environment. Although no clear difference was revealed in terms of neutral temperature, women seem to be more sensitive to deviations from optimum leading to more to more complains, especially in cooler conditions. This is in the line with the findings of Schellen et al. (2012) who also reported that particularly for females the skin temperature of hands is of high importance for overall thermal sensation in cooler conditions. The lower tolerance of women to the deviations from the optimal temperature range can be explained by the fact that they have compared to men generally smaller total and lean body mass, larger body surface and lower resting metabolic rate, although their greater body fat content should allow them to tolerate lower ambient temperatures better (Kaciuba-Uscilko & Grucza 2001). This is supported by the findings of Tikuisis et al. (2000) who compared thermoregulatory responses of men and women immersed in cold water. No significant differences were found between the two genders when the body fatness and the ratio of body surface area to size are taken into account. Therefore it is necessary to test the proposed personalized heating with the subjects from different subpopulations and relate their subjective as well as physiological response to parameters including gender, weight, height, body mass index or age.

This paper presents initial results and gives future research directions of the applicability of the fingertip temperature as a control signal for personalized radiant heating. The topics for further investigation include:

- The ways how track and measure the fingertip temperature using infrared thermography.
- Verification of the correlation of the fingertip temperature and the overall thermal comfort under mild conditions.
- The individual differences in subjective as well as physiological response to local radiant heating based on factors such as gender, age or body mass index.

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